CEBAF-TH-90-07
WM-90-119

Hadron Spectroscopy

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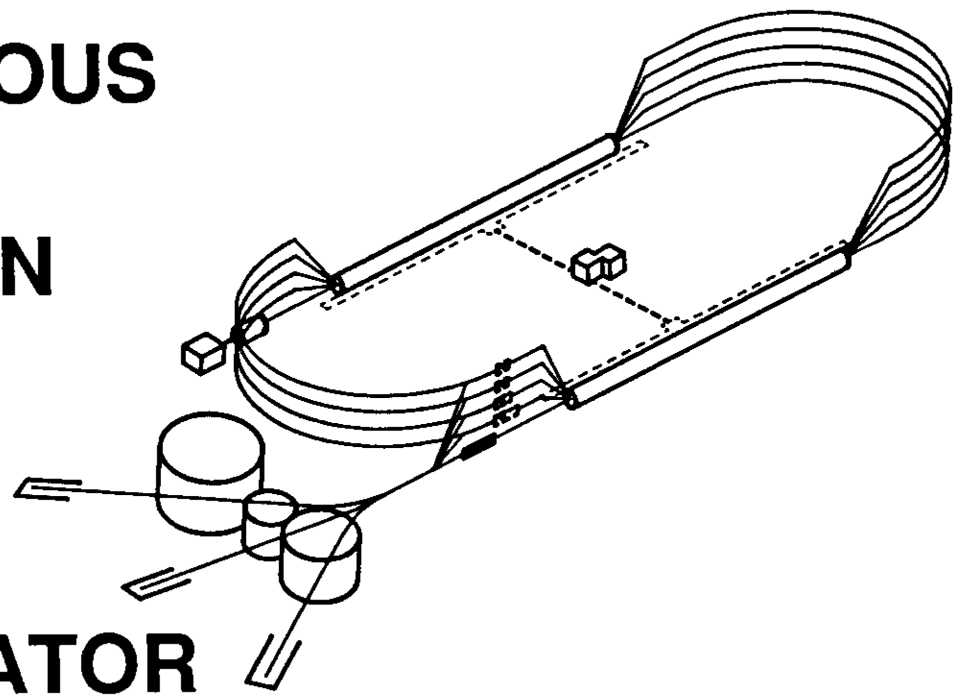

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HADRON SPECTROSCOPY

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This review summarizes contributions to the Parallel Workshop Session on Hadron Spectroscopy at the PANIC XII conference.

1. INTRODUCTION

This review is divided in two parts: sections 2 to 7 deal with new experimental results presented at this workshop. Sections 8 and 9 cover new theoretical ideas and concepts.

New results in meson spectroscopy were presented on the formation of spin-2 particles In section 2 we discuss further evidence by the Crystal Barrel experiment at LEAR for an isoscalar tensor meson at 1560 MeV as well as the observation by the CELLO and Crystal Ball collaborations of two pseudo-tensor states at 1750 MeV and 1900 MeV. The following three sections cover partial wave analyses of the $K\bar{K}\pi$, the $\pi\pi$ and the K^+N final states: section 3 is on the BNL Multiparticle Spectrometer results on $K\bar{K}\pi$ with emphasis on the $\eta/f_1(1440)$ problem, section 4 describes the analysis of $\bar{p}p \to \pi\pi$ by Martin and Oades which shows clear signals for high mass, low spin mesons, and section 4 discusses the search for multi-quark states with hypercharge 2 undertaken in the VPI analysis of K^+N data. Section 6 summarizes the very precise measurement of the electromagnetic form factor of the proton in the time-like region by the PS 170 experiment at LEAR, while a discussion of the presentation by B.Povh on possible systematics of hadronic radii follows in section 7.

Several of the theory contributions were on the subject of, or related to, the problem of understanding the low energy interactions of two hadrons. They are discussed in section 8. Section 9 summarizes some new theoretical results in hadron spectroscopy and structure.

2 SPIN 2 MESONS

2.1 TENSOR MESONS

In 1989 the ASTERIX collaboration observed the production of a new isoscalar $\pi\pi$ resonance[1] at a mass of 1565 MeV and a width of 170 MeV. This resonance was produced in $\bar{p}p$ annihilations at rest into $\pi^+\pi^-\pi^0$ from P states of antiprotonic hydrogen. From the phase motion of the $\pi^+\pi^-$ D-wave they deduced the spin-parity $J^{PC} = 2^{++}$. This state cannot be associated[1] with either $f_2'(1525)$, $f_2(1720)$ or with a radial excitation of the $f_2(1270)$. Thus a likely interpretation is a multi-quark state ($qq\bar{q}\bar{q}$ or $N\bar{N}$).

New results on this resonance were presented by U. Wiedner of the Crystal Barrel collaboration[2]. This experiment[3] at LEAR consists of a finely segmented CsI calorimeter surrounding a jet drift chamber and a proportional chamber in a solenoidal field of 1.5 T. The data presented were taken in December 1989 with a special trigger selecting all-neutral final states. The analysis of events with six photons in the final state reveals clear π^0 and η production in the $m_{\gamma\gamma}$ invariant mass spectra. Selecting $3\pi^0$ events yields the Dalitz plot shown in Fig. 1a. Clear bands are visible at the position of the $f_2(1270)$ meson and the above mentioned $f_2(1565)$. Manifest are also the different angular distributions of these two mesons: the $f_2(1270)$ exhibits approximately a $\cos^2\theta$ distribution, whereas the $f_2(1565)$ seems to be produced according to $\sin^2\theta$. This difference in the production mechanism may also reflect the difference in their quark constituents. Fig. 1b shows the projection of the Dalitz plot. Clear peaks are visible at the mass position of the two tensor mesons. A spin-parity determination has not been presented, but will be available soon.

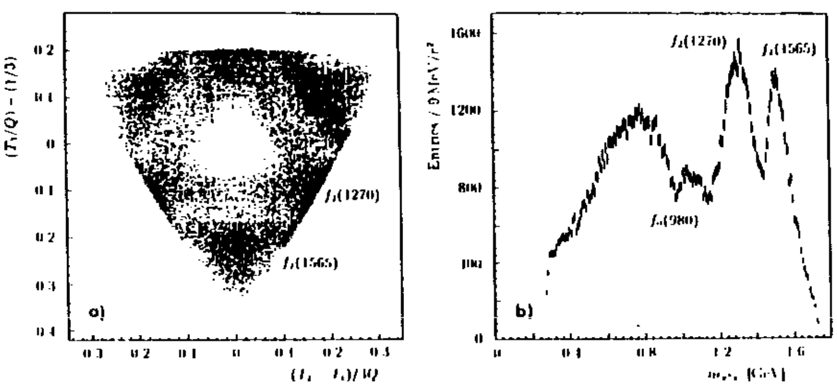

Figure 1: a) $3\pi^0$ Dalitz plot from $\bar{p}p \to 3\pi^0$ events (Crystal Barrel). Six entries per event.
b) Invariant $\pi^0\pi^0$ mass. Evident peaks for $f_2(1270)$, $f_2(1565)$ and indications for the $f_0(975)$ are visible. There are three entries per event.

In addition, the Crystal Barrel collaboration presented preliminary results on $\bar{p}p$ annihilations into the four-photon final state. Clear evidence was shown for the production of the following final states: $\pi^0\pi^0$, $\pi^0\eta$, $\eta\eta$ and $K_S K_L$, where in the latter case the K_L escapes detection. No branching ratios are available yet. The Crystal Barrel collaboration hopes to record more than 10^7 annihilations this year. Such a big data set should help in identifying the nature of many other controversial mesons (e.g. the scalar mesons, the $E/\iota(1440)$ puzzle, exotic J^{PC} states like 1^{-+}, glueballs and hybrids).

2.2 PSEUDO-TENSOR MESONS

The nonet of pseudo-tensors with $J^P = 2^-$ is incomplete: the only established states[4] are the $\pi_2(1670)$ and $K_2(1770)$ mesons, both observed in diffractive production on nuclei. New results concerning pseudo-tensor states were presented by K. Karch (representing the Crystal Ball collaboration).

In 1989 the two collaborations Crystal Ball and CELLO presented evidence for the observation of the $\pi_2(1670)$ in two-photon scattering. Crystal Ball[5] studied the channel $\gamma\gamma \to 3\pi^0$ and found in the $3\pi^0$ invariant mass spectrum an enhancement of about 65 events at a mass of 1740 MeV. Their mass value is about 1.3 standard deviations higher than the value quoted by the Particle Data Group[4]. This mass shift could be explained by final state interactions being smaller in the $\gamma\gamma$ channel. The cross section for this process is shown in Fig. 2a, assuming a decay via $f_2(1270)$. An analysis of the $2\pi^0$ subsystem shows evidence for such a decay sequence, *i.e.*, $\pi_2 \to \pi^0 f_2(1270)$. The spin and parity of the observed state is found to be consistent with $J^P = 2^-$ from an investigation of decay angular distributions. Finally they determine from a fit to the $3\pi^0$ mass distribution the partial width to two photons:

$$\Gamma_{\gamma\gamma}(\pi_2) = (1.45 \pm 0.23 \pm 0.28)\,\mathrm{keV} \qquad \text{(Crystal Ball)}.$$

The CELLO collaboration analyzed[6] the reaction $\gamma\gamma \to \pi_2 \to \pi^+\pi^-\pi^0$, which is complicated by the fact that in addition to a strong $a_2(1320)$ signal two intermediate states contribute and interfere: $\pi^0 f_2(1270)$ and $\pi^\pm\rho^\mp$. Depending on the relative phase they obtain a two-photon partial width of

$$\Gamma_{\gamma\gamma}(\pi_2) = (0.8 \pm 0.3 \pm 0.1)\,\mathrm{keV} \qquad \text{(CELLO)}$$

for constructive interference (which is preferred by the data) and $\Gamma(\gamma\gamma) = (1.3 \pm 0.3 \pm 0.2)$ keV assuming incoherence. Destructive interference has been ruled out. The mass value $m(\pi_2) = 1684 \pm 82$ MeV which CELLO extracts from their data is in good agreement with that of the Particle Data Group.

The Crystal Ball detector has also been used to measure[7] the $\eta\pi^0\pi^0$ mass spectrum in the reaction $\gamma\gamma \to 6\gamma$. The spectrum shown in Fig. 2b is dominated by 270 η' events, for which the partial width was determined to be $\Gamma_{\gamma\gamma}(\eta') = (0.36 \pm 0.02 \pm 0.03)$ keV, in good agreement with previous measurements[4]. In addition, they observe an enhancement of about 34 events in the cross section near 1900 MeV which is attributed to the two-photon production of a new resonance. The small number of events does not permit

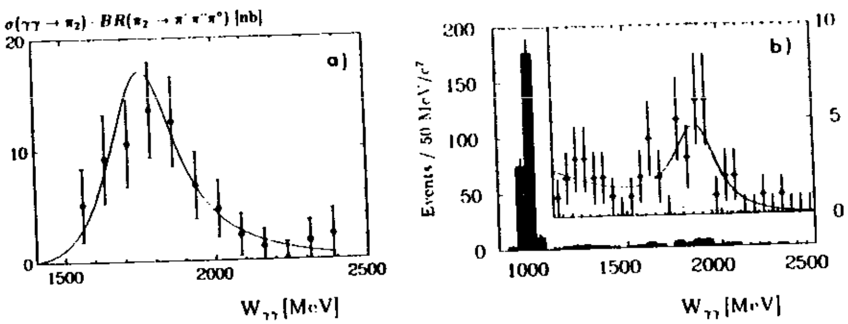

Figure 2 a) The cross section $\sigma(\gamma\gamma \to \pi_2) \cdot BR(\pi_2 \to 3\pi^0)$ (Crystal Ball), as a function of the $\gamma\gamma$ invariant mass W. The solid curve results from a Breit-Wigner fit.
b) The invariant mass distribution of $\eta\pi^0\pi^0$ events (Crystal Ball). The insert shows the distribution of events above the strong η' peak. The full line is a fit to the data with Breit-Wigner and background components.

a study for the presence of more than one resonance. On the basis of its mass and the related observation of the π_2, this resonance might be the $J^{PC} = 2^{-+}$ η_2 meson with dominant quark content $s\bar{s}$ (see Ref. 8), but other assignments like 2^+ and 0^- are under investigation. When they assume an η_2 decay the $\eta\pi^0$ invariant mass subsystem is best described by a mixture of about 70% $a_2(1320)\pi^0$ and 30% $a_0(980)\pi^0$. The angular distributions of the η direction and the normal of the decay plane (with respect to the beam direction) are both consistent with the decay of an η_2 meson and are inconsistent with 3-body phase space decay. The resonance parameters extracted for an η_2 are:

$$
\begin{aligned}
M(\eta_2) &= (1876 \pm 35 \pm 50)\ \text{MeV} \\
\Gamma_{tot}(\eta_2) &= (228 \pm 90 \pm 34)\ \text{MeV} \quad \text{(Crystal Ball)} \\
\Gamma_{\gamma\gamma}(\eta_2)\text{BR}(\eta_2 \to \eta\pi\pi) &= (0.9 \pm 0.2 \pm 0.3)\ \text{keV}.
\end{aligned}
$$

The observed value of the two-photon partial width is consistent with that expected for a normal $q\bar{q}$ meson. We note, however, that the $a_2(1320)\pi$ decay does not favor the required $s\bar{s}$ assignment of this state.

CELLO has also observed[9] an enhancement in the cross section for $\gamma\gamma \to \eta\pi^+\pi^-$. Their preliminary analysis yields a mass of 1850 ± 50 MeV, a total width of $\Gamma_{tot} = (380 \pm 50)$ MeV and a partial width of $\Gamma_{\gamma\gamma} BR(\eta_2 \to \eta\pi\pi) = (3 \pm 1)$ keV. The spin-parity analysis favors below a mass of 1850 MeV a spin-parity $J^P = 2^-$ state which decays via $a_2\pi^0$, whereas at higher masses they find a major 0^- component decaying to $\epsilon\eta$.

Higher statistics are obviously necessary to unambiguously resolve the mass spectrum, the decay mechanism and the spin-parity of the state(s) decaying to $\eta\pi\pi$ in this mass range. Note that this state may have been observed earlier[10] by the LASS collaboration in a partial wave analysis of $K\bar{K}\pi$ events produced in the reaction $K^-p \to (K_S K^\pm \pi^\mp)\Lambda$. The intensity of the 2^- wave seen in this experiment peaks at around 1860 MeV.

3. PARTIAL WAVE ANALYSIS OF $K\bar{K}\pi$

The 1.4 to 1.5 GeV mass region of non-strange mesons is a subject of great controversy. Various experiments studying the $K\bar{K}\pi$ and $\eta\pi\pi$ final states have observed[4] states near 1420 MeV with spin-parities 0^{-+} or 1^{++}. The pseudoscalar state seems to be produced in radiative J/ψ decays and in most peripheral interactions. The axial-vector state is however produced in hadronic J/ψ decays, in central production experiments and in tagged photon-photon formation experiments. New information regarding these states was presented by J. Dowd of the BNL Multiparticle Spectrometer.

He presented results of a partial wave analysis of the $K^+K_S\pi^-$ system produced in K^-p interactions at 8 GeV/c. This analysis is based on about 2000 events in the mass region up to 1.64 GeV. It complements their previous analyses[11] of the $K\bar{K}\pi$ system using pion and antiproton beams, where they observed in the 1.4 GeV mass region a strong 0^{-+} resonance and possibly a small 1^{++} resonance. In the present analysis they find in addition to a small 0^{-+} $\eta(1280)$ an indication of two peaks in the 0^{-+} $a_0(980)\pi$ wave between 1.4 and 1.5 GeV. This result is similar to that obtained from their π^-p data. The presence of two 0^{-+} states in the 1.4 GeV mass region has recently also been claimed by the Mark III collaboration[12], one state at 1416 MeV decaying via $a_0\pi$ and another at 1490 MeV decaying via $K^*\bar{K}$. Both mass values are consistent with the BNL-MPS values.

The strongest wave 1^{+-} is consistent with a resonance below threshold. The 1^{++} wave on the other hand shows neither in the 1.4 GeV nor in the 1.5 GeV region indications of resonant behavior. For the 1^{++} $K^*\bar{K}$ wave Mark III finds[12] an enhancement at 1443 MeV, a mass significantly higher than that measured in two-photon[13] and central production[14]. More data is obviously needed to test for the hypotheses of the $f_1(1420)$ being a $K^*\bar{K}$ molecule[15] and the $f_1(1530)$ being the isoscalar partner of $f_1(1285)$.

4. PARTIAL WAVE ANALYSIS OF $\bar{p}p \to \pi\pi$

Studying high mass resonances in hadronic interactions is in general very difficult due to the production of very many spin states which overlap. In addition, the states which lie on the leading Chew-Frautschi trajectory are produced most strongly and thus the properties of other states is difficult to establish. However, the reaction $\bar{p}p$ at low momenta will preferentially form mesons with relatively low spins due to the centrifugal barrier. Thus $\bar{p}$ annihilations provide a means of studying high mass, low spin states.

G.C. Oades presented a partial wave analysis for the process $\bar{p}p \to \pi^+\pi^-$ and $\bar{p}p \to \pi^0\pi^0$ in the center-of-mass range from 1.9 GeV to 2.5 GeV. In a first step Martin and Oades prepared[16] invariant amplitudes making use of the general properties of analyticity and crossing symmetry. A largely model-independent scheme was constructed which combined these properties in the form of parametric hyperbolic dispersion relations. In the next step, these amplitudes have been used to explore the resonant content of these amplitudes. The advantage of this method is that the phase of the amplitudes has to agree with values reconstructed from phase shifts in the crossed $\pi N \to \pi N$ channel. Furthermore this method yields unique solutions and is nearly model-independent, in contrast to earlier studies. Finally, Argand diagrams have been examined for resonance activity and fits are made to estimate the resonance parameters.

As an example, Table 1 shows some of the extracted resonance masses in comparison with the predictions by Godfrey and Isgur[8]. It should be noted that the $0\ 4^{++}$ result clashes somewhat with the tabulated[4] mass of 2047 ± 11 for the $f_4(2050)$, while its $\pi\pi$ decay make the $s\bar{s}$ interpretation unlikely. The mass of the $0\ 2^{++}$ state also seems high for an ω-like $^3P_2$ state if one accepts the conventional wisdom that spin-orbit splittings are small: the established $f_4(2050)$ and the claimed $a_4(2040)$ and $a_3(2050)$ all suggest that the F-waves are about 100 MeV lower in mass. The accuracy of these determinations could be improved at low energies by more data from LEAR and KEK. Also an extension to $\bar{p}p \to K\bar{K}$ data, which could help resolve ϕ-like states from ω-like ones, is possible.

Table 1: Resonance masses found in a partial wave analysis of $\bar{p}p \to \pi\pi$ by Martin and Oades, compared to theoretical predictions by Godfrey and Isgur. All masses are in GeV.

$I\ J^{PC}$	Martin & Oades (this meeting)	Godfrey & Isgur (Ref. 8)
$1\ 1^{--}$	2.09 ± 0.02 (predominately $^3D_1$)	$3^3S_1(2.00)$ and $2^3D_1(2.15)$
$1\ 3^{--}$	2.13 ± 0.02 (predominately $^3G_3$)	$2^3D_3(2.13)$ and $1^3G_3(2.37)$
$0\ 2^{++}$	2.16 ± 0.01 (predominately $^3F_2$)	$2^3P_2(2.04)$, $1^3F_2(2.05)$ and $1^3F_2(2.24, s\bar{s})$
$0\ 4^{++}$	2.17 ± 0.01 ($^3F_4$ and $^3H_4$)	$1^3F_4(2.01)$ and $1^3F_4(2.20, s\bar{s})$

5. PARTIAL WAVE ANALYSIS OF K^+N SCATTERING

Several phase shift analyses have been made of the K^+-nucleon system in view of the possible existence of K^+N bound states, which would be multi-quark states with hypercharge 2. Most previous analyses employed the single-energy phase shift technique, where solutions are searched separately at discrete energy points. The final solution is then obtained by requiring a smooth energy dependence to other solutions at different energies.

J.S. Hyslop of VPI presented a simultaneous single-energy and energy-independent analysis of K^+N scattering data with emphasis on isoscalar resonances. A previous analysis[17] by the same group of the isovector channel K^+p revealed three possible resonances (see Table 2). The analysis presented by Hyslop used the initial set of $I = 1$ parameters from Arndt *et al.*[17] The $I = 0$ initial parameters were taken either from Hashimoto's analysis[18] or by building up the solution by successively fitting more and more energy-bins of data. Both ansatz' yield essentially the same results. In Table 2 we show resonance masses found by the VPI group using the first method: in the $I = 1$ sector he confirms the results from Arndt *et al.*[17]. In the $I = 0$ sector he finds two resonances, P_{01} and D_{03}, with, however, smaller masses than those obtained by previous analyses. It is interesting to note that as in previous analyses there is no S-wave resonance structure. The MIT bag model[19] predicts such states with isospin $I = 0$ and 1 at masses around 1.7 GeV and 1.9 GeV. It seems that both much more precise experimental (polarization) data and multichannel analyses including important inelastic thresholds is needed before the question of the existence of hypercharge 2 baryon multi-quark states can be settled.

Table 2: Masses (in MeV) of resonances found by Hyslop and others in partial wave analyses of K^+N scattering data. No mass values have been given in the paper by Hashimoto[18].

$L_{I,2J}$	PDG Ref. 20	Nakajima *et al.* Ref. 21	Hashimoto Ref. 18	Arndt & Roper Ref. 17	Hyslop *et al.* (this meeting)
P_{01}	1780	1778			1545
D_{03}	1865	1907	observed		1767
P_{11}	1725		observed	1725	1729
P_{13}	1900	1931	observed	1780	1812
D_{15}				2160	2092

6. PROTON ELECTROMAGNETIC FORM FACTOR

A precise measurement of the electromagnetic form factor of the proton in the time-like region has been carried out at LEAR by the PS 170 collaboration[22] and was presented by E. Mazzucato. They used the rare process $\bar{p}p \to e^+e^-$ with incoming antiprotons of momenta between 0 and 900 MeV/c. These momenta allowed them to scan the kinematical range from threshold $q^2 = 4M_p^2$ to 4.2 GeV^2. About 3300 e^+e^- pairs have been observed in addition to 164×10^3 hadron pairs ($\pi^+\pi^-$ and K^+K^-), which are used for normalization purposes.

From an analysis of the angular distributions and a comparison with the theoretical cross section

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 P_{CM} E_{CM}} \left\{ |G_M|^2 (1 + \cos^2\theta) + \frac{4M_p^2}{s} |G_E|^2 \sin^2\theta \right\}$$

they obtain the preliminary result that the electric component and the magnetic component of the form factor do not differ appreciably, as is expected near threshold. Assuming the validity of $|G_M| = |G_E|$ they obtain the proton form factor $|G_p|$ shown in Fig. 3. The

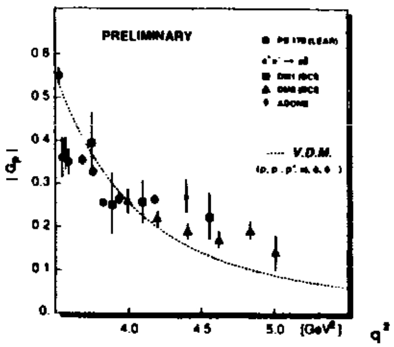

Figure 3: Proton electromagnetic form factor from the PS 170 experiment at LEAR (preliminary).

experimental precision allows a detailed comparison of the measured q^2 dependence with the standard VDM prediction. The apparent deviation of the data from VDM could be explained by either a new 1^{--} resonance at around 2 GeV or by nuclear effects occurring during the $\bar{p}p$ annihilation process.

7. SYSTEMATICS OF HADRONIC RADII

Commonly the radii of hadrons are determined via their interactions with electrons. This procedure yields the mean squared *charge radius* and is available for the proton, pion and kaon. In contrast, the mean squared *strong interaction radius* can be inferred from hadron-proton scattering experiments. B. Povh presented two methods[23] for extracting such strong radii. The first method employs the use of the slope parameter b_{hp} measured in elastic hadron-proton (hp) scattering: $b_{hp} = (1/3)(\langle r^2\rangle_h + \langle r^2\rangle_p)$. This relation follows directly from the t-dependence of the elastic cross section. It is reminiscent of the method of Chou and Yang[24]. The second method uses the following relation between hadron-proton and proton-proton total cross sections

$$\langle r^2\rangle_h \quad = \quad \langle r^2\rangle_p \times \frac{\sigma_{hp}^{tot}}{\sigma_{pp}^{tot}}$$

with input from the first method that $\langle r^2\rangle_p = (3/2)b_{pp} = 0.67\,\mathrm{fm}^2$. The resulting values for some selected hadrons are given[23] in Table 3 together with the electromagnetic radii. The agreement of both radii is very good. It is apparent that the radii get smaller with increasing strangeness or heavy quark content, an effect know from the study of the charmonium and bottonium system. To study this effect, the authors[23] calculate the radii using the non-relativistic quark model and find values which are too small by more than a factor of two. To remedy this deficiency they add to the result of the nonrelativistic calculation a radius $\langle r_q^2\rangle \simeq \langle 1/m_q^2\rangle$ for each constituent quark in the hadron. With the exception of the pion they then obtain good agreement with experimental radii, see Table 3.

Table 3: Experimental values[23] for the mean charge and strong interaction radii $\langle r^2\rangle$ in units of fm^2. The theoretical calculation is explained in the text, see also Ref. 23.

hadron	p	Λ,Σ	Ξ	π	ρ,ω	K^+	ϕ
Strong $\langle r^2\rangle$	$.67 \pm .02$	$.58 \pm .02$	$.50 \pm .02$	$.41 \pm .02$	$.52 \pm .05$	$.35 \pm .02$	$.21 \pm .02$
Charge $\langle r^2\rangle$	$.67 \pm .02$			$.44 \pm .01$		$.34 \pm .05$	
Theory $\langle r^2\rangle$	.67	.55	.44	.54	.54	.40	.25

8 SUBSTRUCTURE IN FORM FACTORS AND SCATTERING

Jaffe presented the results of a study[25] which may be a watershed in the analysis of the role of quarks in determining hadronic form factors and scattering amplitudes. The new insight arises from resolving an old puzzle in heavy quarkonia. Consider heavy versions U and D of the u and d quarks with $m_U = m_D \equiv m_Q \gg \Lambda_{QCD}$. Then the ground state of the $U\bar{D}$ system is nonrelativistic and Coulombic with a radius $r_{Bohr} \sim (m_Q\alpha_s)^{-1}$, and it is obvious that its charge radius $r_{em} \sim r_{Bohr}$. However, this conclusion seems to be at odds with dispersion theory. Since the singularities in the complex momentum transfer plane begin along the positive real axis at $q^2 \simeq 4m_Q^2$ corresponding to the vector meson poles [1*], dispersion theory sets a scale for the charge radius corresponding to $r_{em} \sim m_Q^{-1}$, a factor α_s too small.

In Ref. 26 it was speculated that the resolution of this mismatch would lie in the consideration of anomalous thresholds [27]. (Recall that a similar paradox arose in the case of the deuteron electromagnetic form factor, where the nearest singularity along the positive real q^2 axis is at $4m_\pi^2$, but where $r_{em} \sim (m_N E_B)^{-1/2} \gg (2m_\pi)^{-1}$, corresponding to the size of the deuteron wavefunction ($E_B = 2.2$ MeV is the deuteron binding energy). The existence of this threshold only 2.2 MeV above the deuteron produces new singularities on other sheets of the complex q^2 plane which dominate the form factor near $q^2 = 0$.) Jaffe's new result shows that this is exactly what is going on: even though the quarks are confined so that there are no actual thresholds and therefore no anomalous

[1*] There is also a cut beginning at approximately $16m_Q^2$, *etc*. We are ignoring for simplicity the inessential complication that in fact poles and cuts corresponding to glueballs will also exist.

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